HABITABLE PLANETS

ORIGINS

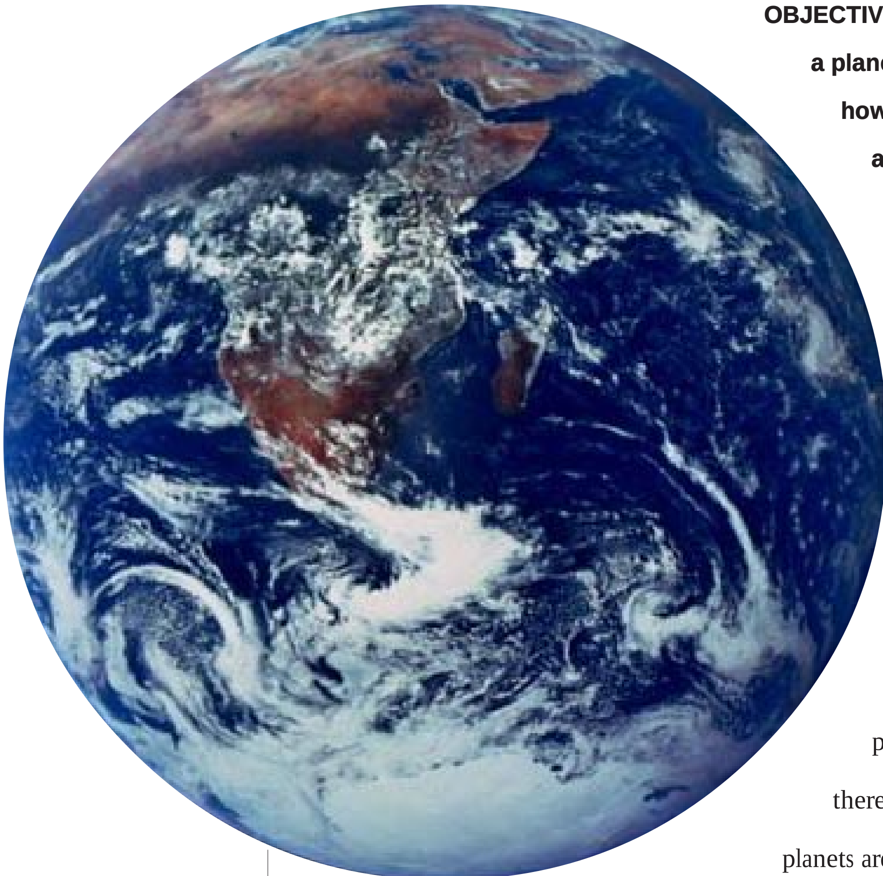
S C I E N T I F I C   G O A L S

Planets serve as cosmic petri dishes, places where life, once begun, can potentially flourish. In those cases where life has flourished, it is reasonable to suppose that it has left its mark on many facets of its home planet. The part of a planet that is most likely to carry the detectable imprint of life on the planet is its atmosphere.

Some 2 billion years ago, and roughly 2 billion years after Earth formed, the composition of Earth's atmosphere changed in a fundamental way. There was a significant increase in the amount of molecular oxygen (O_2) present in the atmosphere. This increase is thought to be due mainly to photosynthesis by a sufficiently large mass of living material on the planet.

The importance of this increase — both for the future of life on Earth, and for what it may say about how life can alter planetary atmospheres elsewhere — cannot be overestimated. However, the presence of molecular oxygen should not be considered the only signature of life. Life first appeared on Earth within 700 million years after Earth formed. Perhaps a billion years passed before the increasing biomass on the young Earth was able to alter the composition of the planet's atmosphere. What would be the signature of this primitive life, and how would we detect it remotely if it were occurring now on a planet revolving around another star? Such life almost certainly will take evolutionary pathways that differ from the one taken on Earth. What alternative signatures might we expect, and again, how would we detect and then interpret evidence that we may obtain from telescopic observations of other planetary systems?

3 TO DETERMINE WHETHER HABITABLE OR LIFE-BEARING PLANETS EXIST AROUND OTHER STARS IN THE SOLAR NEIGHBORHOOD.



OBJECTIVE 5 • Determine what makes a planet habitable and determine how common habitable worlds are in the Universe.

Where should we look for habitable planets? Based on our only example (life on Earth), the minimum prerequisites for life are liquid water, certain cosmically abundant elements, and a source of energy to drive complex chemical reactions. We must therefore determine what sorts of planets are likely to have liquid water and how common they might be. Understanding the origin of water on the planets and satellites of the Solar System will yield insights into the ways water might be distributed within an emerging planetary system. Research on climate changes in response to changes in energy input such as solar variability, radioactive decay, or tidal heating will reveal the long-term habitability of a planet. Studying the processes of planet formation and surveying a representative sample of planetary systems will help us determine what types of planets are present and how they are distributed — essential knowledge for judging the frequency of habitable planets.

An Image of a habitable (inhabited) planet seen by the Apollo astronauts.

INVESTIGATIONS FOR OBJECTIVE 5

Investigation 9: Determine the ultimate outcome of the planet-forming process around other stars.

Because of our working assumption that life is a planetary phenomenon, we must understand the planet-forming process of potentially habitable planets. As part of Investigation 9, astronomers will determine, in a statistically valid manner, the distribution of planets and planetary orbits and masses for gas-giant planets around a wide variety of stars having a range of physical properties. To address the question of planet habitability, we must conduct an extensive census of mature systems to determine the orbital characteristics and gross physical properties of extrasolar planets of all masses and compositions (not just the gas giants). In particular, we need to make a complete inventory of all nearby stars to find all detectable planets in orbit around them. The planets will be about a billion times fainter than the stars in reflected visible light and a million times fainter in thermal infrared emission. A survey of carefully selected samples of more distant stars will reveal the dependence of the formation of potentially habitable planets on stellar properties such as mass, heavy-element abundance, angular momentum, and magnetic field. These stellar properties may also tell us when the earliest planets formed in the history of the galaxy, and hence place important upper limits on when the earliest life in the galaxy may have arisen. Determination of the frequency and orbital characteristics of potentially habitable Earth-size planets is of particular importance.

SIM and TPF are well poised to help fulfill and complete this investigation. SIM's thousandfold gain in astrometric accuracy over current techniques will be able to detect nearly Earth-mass planets around the nearest stars and yield the first reconnaissance of the solar neighborhood for planets in the Uranus–Neptune mass regime. SIM will provide the input data into TPF, which will then complete the census of companions, including potentially habitable planets around the nearby stars. LF will have the capability to make high-spectral-resolution studies of these important molecular species as well as to find weaker species that are unambiguously indicative of life. For the first time, we will have a census of planetary systems in our environs in the Galaxy.

Investigation 10: Define climatological and geological effects upon the limits of habitable zones around the Sun and other stars to help determine the frequency of habitable planets in the Universe.

The development of life on the early Earth provides clues to the possible evolution of life elsewhere.

The astronomical search for life is concerned with habitable planets, defined as those where liquid water can exist on the surface. Other types of bodies — for example, Jupiter's moon, Europa — might have subsurface liquid water and perhaps subsurface

life as well, but the life zones on such bodies are far more difficult to be examined remotely. The size and location of a habitable zone varies with the luminosity of a star. A multipronged program will be mounted using ground-based facilities and SIM to detect potentially habitable planets in sufficient numbers so as to understand their distribution and help guide the development of the future large spaceborne interferometers (TPF and LF). Theoretical models of the processes that lead to the origins of habitable planets must be developed to understand the role of the geological processes, such as plate tectonics and vulcanism, and global climate changes, that affect the origin and early evolution of life. Analyses of extraterrestrial samples, such as meteorites or cometary dust from the Stardust mission, will continue to help us constrain these models.

These theoretical and laboratory-based efforts are a key component of the R&A program, and they will provide critical understanding to be applied to the SIM/TPF planetary census of the solar neighborhood. The ultimate outcome will be the specific identification of potentially life-bearing planets. The spectroscopic capability of TPF will then determine whether planets in habitable zones actually possess atmospheres congenial to life, possibly discovering spectral signatures indicative of active biospheres.

OBJECTIVE 6 • Establish how to recognize the signatures of life on other worlds.

We are now beginning to search for life, past and present, on a variety of worlds. This search requires that we be able to recognize extraterrestrial biospheres and to detect the signatures of extraterrestrial life. Within the Solar System, and based on our experiences here on Earth, we must learn to recognize structural fossils or chemical traces of extinct life that may be found in extraterrestrial rocks or other samples. To understand remotely sensed information from planets orbiting other stars, we should develop a catalog of possible signatures of life.

INVESTIGATIONS FOR OBJECTIVE 6

Investigation 11: Describe the sequences of causes and effects associated with the development of Earth's early biosphere and the global environment.

The events that connect biological and environmental evolution, and the forces that have sustained them, are either unknown or poorly characterized. To develop a robust, integrated history of the biosphere, we must more accurately determine the times at which biological and geological events occurred, the sequences of the steps involved, and the budgets and distributions of geochemical constituents in the early crust, oceans, and atmosphere.

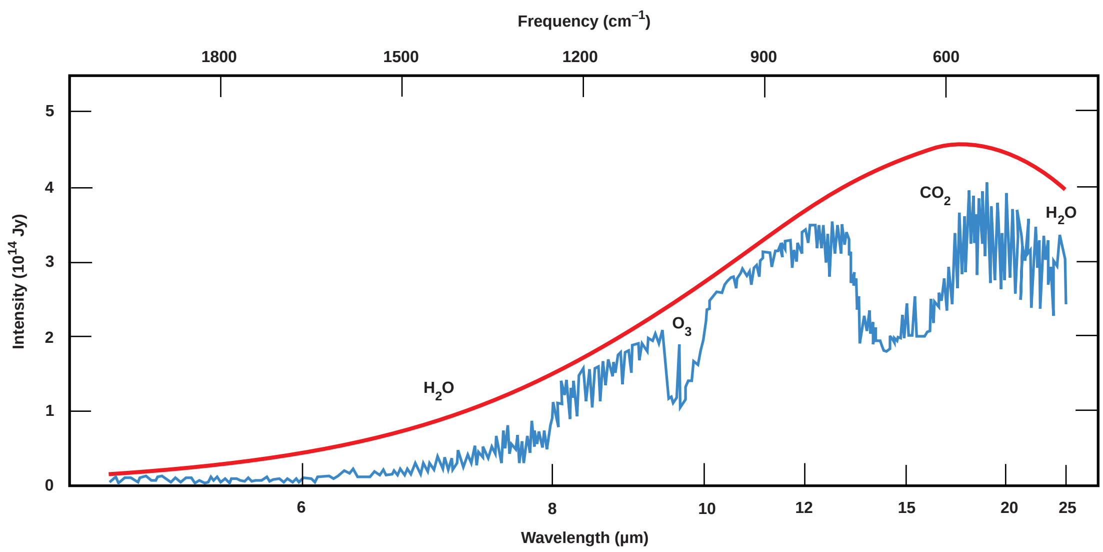
In the near term, we can examine rocks using geochemical and paleontological techniques at levels of detail that allow the dissection of the geologic record of key events in Earth history and the definition and testing of plausible relationships between causes and effects. We can examine living microbes to elaborate the connection between groups of organisms to elucidate the evolution of key enzymes and metabolic pathways that had profound impacts on the environment (e. g., production of biomass and photosynthesis using oxygen). We can reconstruct the development of the biogeochemical cycles of carbon and of its reaction partners. Geologic strata that provide paleobiological information about extreme environments such as hydrothermal systems, aquifers, and dry basins merit special attention. Firmer constraints on early atmospheric composition must be established. Such studies will enhance our ability to recognize the signature of extraterrestrial life in returned samples and in the spectroscopic analysis of distant atmospheres. These are all a focus of the astrobiology component of the R&A program.

Artist: Peter Sawyer, Copyright NMNH, Smithsonian

The oceans and atmosphere formed early in Earth's evolution as a planet. Reconstructing the environmental history of Earth in the first billion years will shed light on the setting for the origin of life.

Investigation 12: Define an array of astronomically detectable spectroscopic features that indicate habitable conditions and/or the presence of life on an extrasolar planet.

According to our present limited understanding, the minimum prerequisites for life are liquid water, certain elements such as carbon, nitrogen, and sulfur, and a source of energy to drive complex chemical reactions. Beyond the Solar System, the search for such conditions is limited to examining the range of distances around nearby stars called the "habitable zone," where the surface temperature on a planet can support liquid water with appropriate atmospheric pressures.



The thermal infrared spectrum of Earth is marked by deep absorption bands of molecules such as water, carbon dioxide, and ozone.

The spectral signatures of molecules can be used to infer the composition and physical conditions in the atmospheres of planets. The mid-infrared wavelengths (7-17 µm) contain strong spectral features of key gases, including CO_2, H_2O, and O_3, that can be detected with modest spectral resolution. The distance of the planet from its parent star, its total IR brightness and temperature, and the strength of the CO_2 and H_2O lines together can provide a rich characterization of a planet's surface conditions. Using TPF, we will be able to obtain infrared spectra of extrasolar planets that are situated within the habitable zones of the few hundred solar-type stars within approximately 15 pc (approximately 50 light years) of our own Solar System.

Accordingly, we must develop the framework for interpreting these spectra, both for evidence of habitable conditions (e.g., the presence of liquid water) and for evidence of life. Aspects of the strategy include developing appropriate observational approaches that optimize sensitivity and spectral and spatial resolution, creating models of atmospheric chemistry and its evolution, and achieving an understanding of the factors that control the composition of biological gas emissions into the atmosphere. We must develop the ability to discriminate between those environmental conditions and gas compositions that indicate a geologically active, but "lifeless," planet versus those conditions and compositions that compel a biological interpretation.